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(54) COLD CATHODE STRUCTURE

(71) We, GENERAL ELECTRIC COMPANY, a corporation organized and existing under the laws of the State of New York, United States of America, of 1 River Road, Schenectady 12305, State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to a cathode structure and is concerned with cathode structures which emit electrons, usually into a vacuum, without the generation of a significant amount of heat. Such cathodes are known as cold cathodes. The invention also relates to an electron discharge device having such a cathode.

Most present day vacuum tubes employ thermionic or hot cathodes as a source of electrons. These cathodes however consume a considerable amount of power in heating the cathode and hence produce a considerable amount of heat and/or light which often interfere with the operation of the tube. Additionally, due to the thermal capacity of the cathode, the flow of electrons cannot be conveniently controlled at the cathode and hence a separate control grid electrode is required to control the electron flow to an anode. The control grid, however, lacks high sensitivity and does not permit the full use of the current output from the cathode. Still another disadvantage of a hot cathode is its limited lifetime.

To overcome the difficulties of the thermionic cathode devices, a number of cold-cathode devices have been proposed. Cold-cathode devices emit electrons without a significant increase in temperature. Three such devices are the field-emission cathode, the tunnel cathode and the semiconductor cathode. The field-emission cathode is use primarily in special purpose applications, but its use is limited by its instability and the requirement of very high voltages. The tunnel diode uses the tunnelling of electrons through a thin dielectric to achieve the energy necessary for ejection of electrons into the vacuum. Although much research has been done on this device, its efficiency is still very much lower than that of the hot cathode.

The semiconductor cathode makes use of the built-in voltage of a P-N junction or a Schottky barrier to raise the energy of the electrons sufficiently to overcome the vacuum barrier. Since this build-in voltage is usually only a few electron volts, surface treatment is required to lower the vacuum barrier. One such device is described in *Applied Physics Letters* by Williams and Wronski, Vol. 13, No. 7, October 1, 1968. A similar device is described by Geppert in U.S. Patent No. 3,150,282. These devices, however, exhibit very low emission efficiencies, i.e., the ratio of emitted electron current to the current flowing between the electrodes of the semiconductor.

In both of the aforementioned devices, a major source of inefficiency is the loss of electrons (due to recombination) in the p-type side of the P-N junction or in the metal electrode in the case of the Schottky barrier device. While the Schottky barrier metal electrode can be made very thin (less than 100 Angstroms thick) to minimize this effect, such films tend to be discontinuous, are not homogeneous and do not provide an efficient structure for the emission of electrons.

The present invention is thus generally concerned with cold cathodes and can be put into practice to provide a cathode structure operable with good efficiency.

Broadly the present invention provides a cathode structure comprising a semiconductor substrate of n-type conductivity; an arrangement of conductors overlying one surface of

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said substrate and delineating electron-emissive areas of said one surface between said conductors; an arrangement of surface-adjacent p-type regions formed in said substrate in correspondence with and underlying said conductor arrangement to provide a potential barrier to the flow of electrons to said conductors, when the cathode structure is biased into operation, which barrier is greater than the potential barrier at or adjacent said emissive surface areas to the flow of electrons for emission therefrom.

The cathode structure is biased into operation by applying a voltage between the conductor network (positive) and the n-type substrate (negative). The mobile electrons thereby generated in the substrate move toward the said one surface and those electrons of sufficient energy at the emissive areas of this surface are emitted. The relatively high potential barrier created by the p-type regions underlying the conductor arrangement inhibits the mobile electrons flowing to the conductors.

It is preferred to coat the said one surface of the substrate and the overlying conductor arrangement with a low work function material which will enhance emission from the emissive areas. A preferred material for the semiconductor substrate is one from the group consisting of zinc sulphide, gallium arsenide, gallium phosphide and silicon carbide.

In one embodiment of the invention surface-adjacent regions of p-type conductivity are formed in the substrate adjacent the emissive areas of the substrate. These latter regions extend to a depth below the said one substrate surface which is substantially less than the depth to which the above-mentioned arrangement of p-type conductivity regions extends. It is preferred that the depth of these p-type regions adjacent the emissive areas be not more than 300 Angstroms.

The invention and its practice will be better understood from the following description taken in connection with the accompanying drawings, in which:

Figure 1 is a perspective view of a cold cathode structure having a network of conductors disposed on a semiconductor substrate.

Figure 2 is a partial cross-sectional view taken along the lines 2—2 of Fig. 1;

Figure 3 is an energy diagram of the forwardly biased cathode structure illustrated in Figs. 1 and 2;

Figure 4 is a partial cross-sectional view of a cathode structure embodying the present invention;

Figure 5 is an energy diagram of the forwardly biased cathode structure of Fig. 4;

Figure 6 is a partial cross-sectional view of another cathode structure embodying the invention; and

Figure 7 is an energy diagram of the forwardly biased cathode structure illustrated in Fig. 6.

Figures 1 to 3, which do not embody the present invention are used to illustrate one form of cathode structure to which the invention is applicable and the manner in which the structure operates. The following discussion of the cathode structure of Figures 1 and 2 will provide a starting point from which to explain the teachings of the present invention.

Figure 1 illustrates a semiconductor cold cathode 10 comprising a large band gap semiconductor substrate or wafer 12 of n-type conductivity, such as, zinc sulphide, gallium arsenide, gallium phosphide, silicon carbide, or other semiconductors having band gaps greater than approximately 1.2 electron-volts the upper planar surface of substrate 12 is provided with a low resistivity metal contact pad 14, such as gold or silver, insulated from the surface of the substrate 12 by a layer of dielectric material 16, such a vapour deposited silicon nitride, silicon dioxide, magnesium fluoride or any of the other well-known dielectrics used in semiconductor fabrication. Over the surface of the semiconductor substrate 12 is a heterogeneous network of conductors 18 with open spaces 20 therebetween. The conductors 18 may, for example, comprise fine strips of high work function metal, such as palladium, silver, gold or platinum formed in such a manner (e.g., vapor deposition) as to make electrical contact with the metal pad 14 and the surface of the semiconductor substrate 12.

Fig. 2 is a partial cross-section of the cold cathode illustrated in Fig. 1 and more clearly depicts the heterogeneous network of conductors 18 and open spaces 20 with electrons being emitted from the areas of the substrate 12 lying in open spaces 20 between the conductors. Fig. 2 also illustrates the presence of a low work function surface layer 26, such as cesium, which is preferably deposited over the surface of the conductors and the areas therebetween.

The emission of electrons from the cold cathode 10 is achieved by providing a difference of potential between the semiconductor substrate 12 and the conductors 18. As illstrated in Fig. 1, this is readily achieved by providing a voltage source 22 such as a battery with its positive terminal connected to the metal contact pad 14 and thus to conductors 18 and its negative terminal connected to the semiconductor substrate 12. In actual operation of such a device, the cold cathode 10 is preferably enclosed in an evacuated enclosure, such as, for example, a conventional vacuum tube, with a collector electrode spaced at a distance from the cathode for collecting the electrons emitted therefrom. As illustrated in Fig. 2, upon application of a forward bias voltage, electrons are emitted

from the surface of the semiconductor 12 in the open spaces 20 with good efficiency.

The manner in which electrons are emitted from the cold cathode structure illustrated in Figs. 1 and 2 can be more readily appreciated by reference to Fig. 3 which illustrates a potential energy diagram. More specifically, Fig. 3 is a cross-sectional diagram of energy level (E) on the vertical axis and displacement (X) normal to the upper cathode surface on the horizontal axis. The figure illustrates the potential barrier existing at the interface of the semiconductor 12 and the heterogeneous network with an operating bias voltage applied therebetween. The dashed line E_f, illustrates the Fermi level of the semiconductor. Curve A illustrates the potential barrier in the semiconductor 12 adjacent one of the conductors 18, while Curve B is the corresponding potential barrier in the semiconductor adjacent to one of the open spaces 20, where the low work function coating 26 contacts the semiconductor 11. Because of the difference in work functions between the low work function coating 26 and the conductors 18, the barrier illustrated by Curve A is higher than that of Curve B. As a result, very little current flows to the conductors 18, while nearly all of the current flows in the open spaces 20 between the conductors. At this point, a large fraction of the electrons leave the surface of the semiconductor and pass into the vacuum because the low work function coating 26 lowers the surface barrier, the top of the barrier illustrated by Curve B being higher than the vacuum energy level, E_v, which is equal to the energy of an electron at rest in the vacuum outside the semiconductor surface. In other words, the semiconductor has acquired a negative electron affinity as a result of the application of the low work function coating.

Some electrons which reach the semiconductor surface are not emitted into the vacuum and must be conducted back to the conductors 18 so as to prevent a charge build-up at the surface of the semiconductor. This conductivity may be provided by the surface states of the semiconductor 12 or by the low work function coating 26. In instances where high current densities of electrons are required, it may be desirable to employ a thin metal film between the surface of the semiconductor 12 and the low work function coating 26 to further reduce the possibility of a charge build-up.

A typical cold cathode structure of the kind above described may comprise a semiconductor substrate 12 of n-type zinc sulfide; the dielectric 16 may be evaporated magnesium fluoride, the metal pad 14 may be evaporated silver, conductors 18 may be evaporated palladium, while the low work function coating 26 may be alternate layers of cesium and oxygen, preferably with an excess of cesium.

Fig. 4 illustrates an enlarged cross-sectional view of an embodiment of the invention which may take the same general physical configuration as that illustrated in Fig. 1. Fig. 4 is a partial cross-section corresponding to Fig. 2 but shows in addition the provision of p-type regions 28 formed in the semiconductor substrate 12 in a pattern corresponding to and underlying that of the conductors 18. These regions 28 can very readily be produced by appropriately selecting the conductors 18 of a material which diffuses into the semiconductor 12 (at diffusion temperatures) and acts as an acceptor dopant in the semiconductor substrate 12.

The effect of the p-type regions 28 is to reduce still further, the amount of current conducted by the conductors 18 and thereby increase the efficiency of electron emission. This situation is illustrated more clearly by the energy diagram of Fig. 5 wherein the Curve C illustrates the large potential barrier produced in the semiconductor substrate 12 in front of each conductor commencing at the interface between the underlying p-type region and the remaining n-type substrate which extends to the emissive areas 20. Curve B illustrates the smaller barrier in the open spaces over which the emitted electron current flows, the same as in Fig. 3.

Still greater efficiencies of emission can be obtained in accord with yet another embodiment of the invention illustrated in Fig. 6. In this embodiment of the invention, in addition to the opposite-type-conductivity regions 28 described above, additional surface-adjacent regions 30 also of p-type conductivity, are formed at the emissive surface areas of the semiconductor substrate 12, i.e. at the open spaces 20 between the conductors 18. These additional regions 30 are preferably between 10 and 300 Angstroms in depth and are of much lesser depth than that of the regions 28. Regions 30 may typically be produced by the well-known process of ion implantation of impurity atoms into the semiconductor substrate 12.

The operation of the embodiment illustrated in Fig. 6 is best understood by reference to the energy diagram of Fig. 7. In particular, Curve D illustrates the effects of a p-type region 30 on the height of the surface barrier. As illustrated, electrons passing into the vacuum have a higher energy than those passing into the vacuum from the embodiment illustrated in Fig. 4. The height of the barrier illustrated by Curve D is still lower than the barrier illustrated by Curve E but is much higher than that illustrated by Curve B of Fig. 5. The effect of the increased barrier height is to produce a larger negative electron affinity at the semiconductor

surface and thereby increase the fraction of the electrons emitted into the vacuum.

From the foregoing description of the two illustrated embodiments of the invention, it will be readily appreciated that cold cathodes described exhibit high electron emission efficiencies since few electrons are trapped in the heterogeneous network of conductors. Cathodes fabricated in accord with the teachings of the instant invention have many uses in the field of electronics; for example, cathode ray tubes, display devices, microwave generators, amplifiers and information processing devices, to mention only a few.

While certain preferred embodiments have been shown by way of illustration, modifications and changes are possible. For example, the heterogeneous network of conductors and open spaces may take various other configurations than those illustrated such as, for example, gridded, crossed, filigreed, and netted. Further, although the semiconductor material has been described as having a band gap in excess of approximately 1.2 electron-volts, those skilled in the art can readily appreciate that with technological improvements, this value may be lowered. Assuming as above that the cathode is to work in vacuo, in principle any semiconductor may be employed which has a band gap not less than the work function of the emissive areas of the semiconductor substrate relative to a vacuum.

WHAT WE CLAIM IS:—

1. A cathode structure comprising a semiconductor substrate of n-type conductivity; an arrangement of conductors overlying one surface of said substrate and delineating electron-emissive areas of said one surface between said conductors; an arrangement of surface-adjacent p-type regions formed in said substrate in correspondence with and underlying said conductor arrangement to provide a potential barrier to the flow of electrons to said conductors, when the cathode structure is biased into operation, which barrier is greater than the potential barrier at or adjacent said emissive surface areas to the flow of electrons for emission therefrom.

2. A cathode structure as claimed in Claim 1 wherein said semiconductor substrate comprises a material of the group consisting of zinc sulphide, gallium arsenide, gallium phosphide and silicon carbide.

3. A cathode structure as claimed in Claim 1 or 2 wherein surface-adjacent regions of p-type conductivity are formed in said substrate adjacent said emissive areas thereof and extend to a depth below said one substrate surface which is substantially less than the depth to which said aforementioned arrangement of p-type regions extends.

4. A cathode structure as claimed in Claim 1, 2 or 3 further comprising a low work function material overlying said emissive areas.

5. A cathode structure as claimed in Claim 1, 2, 3 and 4 wherein said semiconductor substrate is of a material having a band-gap not less than the work function of the emissive areas of the substrate relative to a vacuum.

6. A cathode structure substantially as hereinbefore described with reference to Figures 4 and 5 or to Figures 6 and 7 of the accompanying drawings.

7. An electron discharge device incorporating a cathode structure which is in accordance with any preceding claim, the structure being disposed for operation in a vacuum.

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Fig. 1.

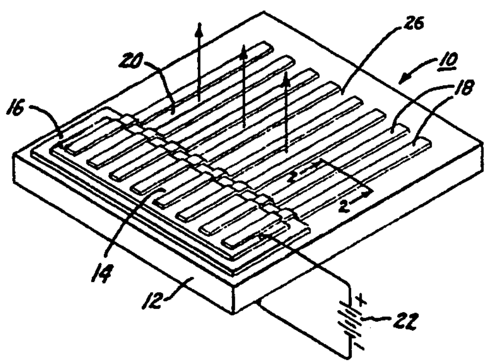


Fig. 2.

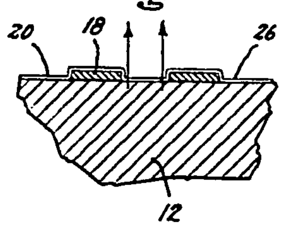
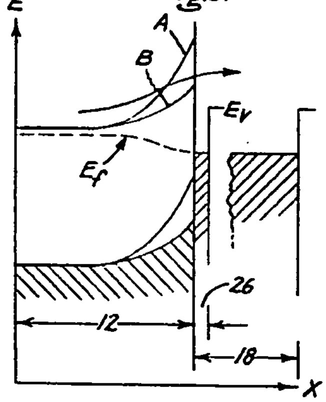


Fig. 3.



1335979 COMPLETE SPECIFICATION

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Sheet 2

Fig. 4.

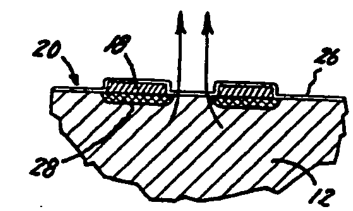

Fig. 5

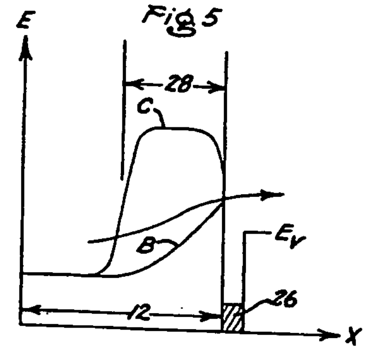

Fig. 6.

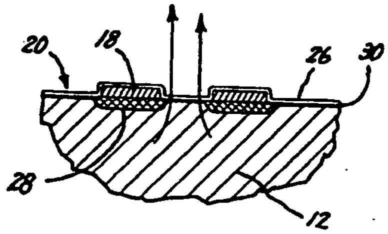

Fig. 7.